APPENDIX C

Virginia Tech Stormwater Design Manual

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1.0 STORMWATER HYDROLOGY

Stormwater hydrology defines the means and methods to calculate stormwater runoff from a designated area. This section documents the hydrologic practices used to establish design flows necessary to prepare the required stormwater peak flow and storage calculations.

1.1 References

Except where more stringent requirements are presented in this Design Manual, stormwater hydrology shall comply with state requirements. The primary design references are:

- VDOT Drainage Manual
- VA Stormwater Management Handbook
- VA Stormwater BMP Clearinghouse website specifications

1.2 Design Frequencies

1.2.1 General

Design frequencies shall be selected consistent with good engineering practice and regulatory requirements. The design frequency requirements in this Design Manual are minimum standards - specific conditions may dictate that less frequent design frequencies should be used.

1.2.2 Storm Drainage Systems

Storm drainage systems consist of open channels, culverts, and storm drains. Designs shall be based on the following minimum design storm frequencies:

Type of System	Frequency
Open Channels: Channel Capacity	10- year
Open Channels: Protective Lining	2- year
Culverts	10-year
Storm Drains	10-year

Additionally, all storm drainage designs for open channels, culverts, and storm drains shall be checked for the 100-year flow condition where there is the possibility of downstream flooding, overtopping primary roads, experiencing significant economic loss, or catastrophic failure. Where justified by the consequences of failure, the minimum design recurrence interval shall be increased.

1.3 Stormwater Management Facilities

Certain stormwater management facilities temporarily store a portion of stormwater runoff to mitigate increases to stormwater runoff peak flows and volumes due to the effects of land development.

1.4 New Development

Channel protection and flood protection shall be addressed in accordance with the criteria set forth in Section 9VAC25-870-66 of the Stormwater Management Regulations.

1.5 Time of Concentration (t_c) and Travel Time (T_t)

1.5.1 General

Travel Time (t_t) is the time it takes runoff to travel from one location to another in a watershed. Travel Time is a component of Time of Concentration (t_c), which is the time for runoff to travel from the most hydraulically distant point in the watershed to the outfall. The Time of Concentration is computed by summing all the travel times for consecutive components of the drainage conveyance system. Travel Time and Time of Concentration generally consist of three flow types – overland flow, shallow concentrated flow, and open channel flow. The following methods shall be used to determine the flow and velocity for the various conditions; however, the results shall be reviewed for reasonableness, and the results shall be revised if needed to provide a reasonable velocity and flow time that will best represent the study area.

When designing a drainage system, the Time of Concentration is not necessarily the same before and after land disturbing activities have been completed. Therefore, the travel time path shall be reflective of the actual conditions both before and after the land disturbing activities.

In some cases, runoff from a portion of the drainage area that is highly impervious may result in a greater peak discharge than would occur if the entire drainage area were considered. In this case, adjustments shall be made to the drainage area by disregarding those areas where the travel time is too long to add substantially to the peak discharge.

To prevent small drainage areas from skewing the time of concentration calculation results, when establishing subdrainage areas for analysis, the largest subdrainage area shall be no greater than 5 times the area of the smallest subdrainage area.

1.5.2 Overland (Sheet) Flow

Overland flow is flow that occurs at the upper end of a watershed, where flow is not concentrated and there are no channels. The length of overland flow shall be reflective of actual conditions and shall normally be no greater than 100 feet.

1.5.3 Shallow Concentrated Flow

Shallow concentrated flow is the flow that occurs when minor rivulets form just downstream from the overland flow. The maximum allowable length for shallow concentrated flow shall be 1000 feet.

1.5.4 Open Channel Flow

Open channel flow occurs where stormwater flow converges in gullies, ditches, and natural or man-made conveyances.

1.5.5 Pipe Flow

Pipe flow is the flow that occurs through culverts and storm drains. Use full-flow pipe velocities, unless it can be shown that the pipe will operate at partially full conditions. If it can be shown that the pipe will operate at a partially full condition, then the partially full pipe velocity may be used.

Design of culverts is presented in Chapter 3. Design of storm drain systems is presented in Chapter 4.

1.6 Hydrologic Methods

1.6.1 General

There are a variety of widely used hydrologic methodologies. Each has its strengths and weaknesses. In the interest of standardizing hydrologic calculations, the following methodologies will be used for all projects, unless a variance is granted. A variance will only be granted if it may be demonstrated that good engineering practice dictates the use of another method.

1.6.2 Peak Discharge Methods for Design of Storm Drainage Systems

The Rational Method may be used to design storm drainage systems for drainage areas up to 200 acres.

The SCS Method may be used for drainage areas up to 10 square miles.

For drainage areas greater than 10 square miles, calculations shall be performed using at least two separate methods as described in the VDOT Drainage Manual (SCS Method, regression equations, and/or stream gage data). The design peak flow shall be selected based on a professional evaluation of the results of the various methods.

1.6.3 Hydrograph Methods for Design of Stormwater Management Facilities

The SCS method must be used to design stormwater management facilities

1.7 Methodologies

Following is an abbreviated discussion of each method. Refer to the VDOT Drainage Manual for a more complete discussion of the Rational Method and the VA SWM Handbook for a more complete discussion of the SCS Method.

1.7.1 Rational Method

1.7.1.1 General

The Rational Method is expressed as:

$$Q = C_fCIA$$

Where:

Q =Peak flow rate of runoff, cubic feet per second (cfs)
C_f =Saturation factor

C =Runoff coefficient representing a ratio of runoff to rainfall (dimensionless) (See VESCH Table 5-2 Below)

I =Average rainfall intensity for a duration equal to the time of concentration for a selected return period (in/hr)

A =Drainage area contributing to the design location, acres (ac)

TABLE 5-2
VALUES OF RUNOFF COEFFICIENT (C) FOR RATIONAL FORMULA

Land Use	C	Land Use	C
Business:		Lawns:	
Downtown areas	0.70-0.95	Sandy soil, flat, 2%	0.05-0.10
Neighborhood areas	0.50-0.70	Sandy soil, average, 2-7%	0.10-0.15
		Sandy soil, steep, 7%	0.15-0.20
		Heavy soil, flat, 2%	0.13-0.17
		Heavy soil, average, 2-7%	0.18-0.22
		Heavy soil, steep, 7%	0.25-0.35
Residential:		Agricultural land:	
Single-family areas	0.30-0.50	Bare packed soil	
Multi units, detached	0.40-0.60	* Smooth	0.30-0.60
Multi units, attached	0.60-0.75	* Rough	0.20-0.50
Suburban	0.25-0.40	Cultivated rows	
		* Heavy soil, no crop	0.30-0.60
		* Heavy soil, with crop	0.20-0.50
		* Sandy soil, no crop	0.20-0.40
		* Sandy soil, with crop	0.10-0.25
		Pasture	
		* Heavy soil	0.15-0.45
		* Sandy soil	0.05-0.25
		Woodlands	0.05-0.25
Industrial:		Streets:	
Light areas	0.50-0.80	Asphaltic	0.70-0.95
Heavy areas	0.60-0.90	Concrete	0.80-0.95
		Brick	0.70-0.85
Parks, cemeteries	0.10-0.25	Unimproved areas	0.10-0.30
Playgrounds	0.20-0.35	Drives and walks	0.75-0.85
Railroad yard areas	0.20-0.40	Roofs	0.75-0.95

Note: The designer must use judgement to select the appropriate "C" value within the range. Generally, larger areas with permeable soils, flat slopes and dense vegetation should have the lowest C values. Smaller areas with dense soils, moderate to steep slopes, and sparse vegetation should be assigned the highest C values.

1.7.1.2 Saturation Factor

The saturation factor (C_f) is an adjustment factor for modifying the runoff coefficient (C) for storms that are less frequent than a 10-year recurrence interval. The product of C_f and C should not be greater than 1.0. Where the product of C_f and C is greater than 1.0, use 1.0.

Recurrence Interval (Years)	C_f
2, 5, and 10	1.0

25	1.1
50	1.2
100	1.25

1.7.1.3 Runoff Coefficient

The runoff coefficient (C) is a variable of the Rational Method that requires significant judgment and understanding for proper selection.

As the slope of the drainage basin increases, the selected C-value should also increase as follows:

- The lower range of C-values should be used where the majority of the slopes are less than 2 percent.
- The average range of C-values should be used where the majority of slopes are 2 to 5 percent.
- The higher range of C-values should be used where the majority of the slopes are greater than 5 percent.

The C-value selection should be based on the soil type as follows:

- The lower range C-values should be used in sandy and other more pervious soils
- The higher range of C-values should be used in clayey and other less pervious soils.

It is often necessary to develop composite C-values based on the different land uses and other factors in a drainage basin. The composite C-value must be representative of the drainage basin. As noted in 1.3.1, averaging the C-value for mixed pervious/impervious watersheds may underestimate the peak flow rate.

1.7.1.4 Average Rainfall Intensity

Rainfall intensity (I) shall be determined by utilizing NOAA or Atlas 14.

1.7.1.5 Drainage Area

Drainage area (A) is measured in acres and is determined from evaluating a topographic map of the area.

1.7.2 SCS Method

1.7.2.1 General

The SCS Method may be used for computing peak flow rates and generating hydrographs for storms of selected return frequencies. This approach takes into account the time distribution of the rainfall, the initial rainfall losses to interception and depression storage, and an infiltration rate that decreases during the course of a storm. 24-Hour Rainfall and Distribution

The 24-hour rainfall is determined by consulting NOAA Atlas 14.

1.7.2.2 Curve Number

The SCS method uses a combination of soil conditions and land use (ground cover) to assign a runoff factor to an area. These runoff factors, or runoff curve numbers (CN), indicate the runoff potential of an area. The CN requires significant judgment and understanding for proper selection.

When calculating existing rates of runoff (pre-construction), assume that all cover types are in good hydrologic condition.

Hydrologic Soils Groups include types A, B, C, and D, with type A being the most permeable and type D the least permeable. Soils maps for Virginia may be obtained by referring to http://soils.usda.gov/.

1.7.2.3 Drainage Area

Drainage areas for each sub-basin should be identified on an appropriate topographic map. The USGS quadrangle maps are often appropriate to delineate drainage areas that extend beyond the site development area.

1.7.2.4 Elevation – Storage Relationship

When runoff hydrographs are being routed through a stormwater management facility, the relationship between the elevation (or depth) of stored water in the facility and storage volume needs to be known and input into the calculation. Often this information is obtained by determining the pond area bounded by contour lines on a grading plan. Enough data pairs (elevation – storage) must be provided to properly model conditions.

1.7.2.5 Elevation – Discharge Relationship

When runoff hydrographs are being routed through a stormwater management facility, the relationship between the elevation (or depth) of stored water in the facility and the discharge rate from the facility needs to be known and input into the calculation. The development of this relationship requires an understanding of the design conditions and underlying hydraulic principles. The hydraulic principles and equations governing the discharge rate will often change several times at varying elevations, based on the flow control and conveyance structures. These include weir flow, orifice flow, culvert inlet control, culvert outlet control, open channel flow, and possible effects from downstream tailwater.

1.8 Pre-Development Conditions

1.8.1 Site Development

Pre-development hydrologic calculations for land disturbing activities shall consider the site conditions that exist at the time that plans for the land development are submitted to SID. Where phased development or plan approval occurs (preliminary grading, demolition, etc.), the existing conditions at the time prior to the first item being submitted shall establish the pre-development conditions.

For the purposes of computing pre-development runoff, all pervious lands on the site shall be assumed to be in good hydrologic condition, regardless of conditions existing at the time of computation.

1.9 Drainage Area Analysis

When determining the stormwater management requirements for quantity control, an analysis of the pre- and post-development site conditions must be conducted. The drainage area analysis shall reflect the ultimate development conditions of the property where the land disturbing activity is being conducted.

To prevent the undersizing of stormwater management components, upstream property conditions in the entire watershed shall be considered in the drainage area analysis. Improvements to stream channels and conveyance systems shall be analyzed based on the ultimate development conditions. Design of drainage infrastructure shall be based on proposed development and the associated density of impervious areas.

When a site contains or is divided by multiple drainage areas, the downstream receiving channel for each area must be analyzed in accordance with section 9VAC25-870-66 of the VSMP regulations.

When a site drains to more than one Hydrologic Unit Code (HUC), the pollutant load reduction requirements shall be applied independently within each HUC, unless reductions are achieved in accordance with a comprehensive stormwater management plan.

The downstream limits of analysis and channel adequacy shall be determined in accordance with section 9VAC25-870-66 of the VSMP regulations.

2.0 OPEN CHANNELS

Open channels are man-made ditches, channels, as well as natural channels, that are used to convey stormwater runoff. This section defines the criteria and restrictions to be used in designing open channels.

Grass Channels are a type of water quality BMP with design requirements beyond those of the typical open channel. The design specifications for Grass Channels can be found on the VA Stormwater BMP Clearinghouse website.

2.1References

Except where more stringent requirements are presented in this Design Manual, open channels shall comply with VDOT and DEQ requirements. The primary design references are the latest editions of the following:

- VDOT Drainage Manual
- VDOT Road and Bridge Standards
- VA Erosion and Sediment Control Handbook
- Hydraulic Engineering Circular Number 15 (HEC-15), Design of Roadside Channels with Flexible Linings

2.2Design Methodology and Criteria

2.2.1 Open Channels

Open channels are classified as either major channels or minor channels. The base design storm for storm drainage systems are the 2- and 10-year, 24-hour storm events, for velocity and capacity. However, the entire system must be capable of handling a 100-year, 24-hour design storm.

2.2.2 Design Flow

Design flow for open channels is contained in Chapter 1. Design flows for open channels must be contained within the channel with adequate freeboard from the top of the bank to the peak water surface elevation. See section 2.2.9 for adequate freeboard requirements for capacity calculations.

Capacity calculations shall be made at the flattest section of the channel.

2.2.3 Hydrology

See Chapter 1 for the methodology used to determine peak flows for a given design frequency.

2.2.4 Channel Hydraulics

Open channel design will be based on Manning's Equation for open channel flow:

$$Q = A \times 1.49/n \times R^{2/3} \times S^{1/2}$$

Where:

Q =Flow rate in the open channel (cfs)

A =Cross-sectional area of the flow in the channel (ft^2)

R =Hydraulic radius, A/wetted perimeter (ft)

S =Channel slope (ft/ft)

n =Channel roughness coefficient (See VDOT Table: Appendix 7D-1 below)

Appendix 7D-1 Values of Roughness Coefficient n (Uniform Flow)

Type of Channel and Description	Minimum	Normal	Maximum
LINED CHANNELS (Selected linings)			
a. Concrete			
1. Trowel finish	0.011	0.013	0.015
2. Float finish	0.013	0.015	0.016
3. Gunite, good section	0.016	0.019	0.023
b. Asphalt			
1. Smooth	0.013	0.013	-
2. Rough	0.016	0.016	-
c. Riprap (st'd VDOT sizes)*			
1. Class 1A	0.033	0.038	-
2. Class 1	0.035	0.040	-
3. Class 2	0.037	0.042	-
4. Class 3	0.039	0.045	-
5. Type I	0.041	0.047	-
6. Type II	0.044	0.050	-
EXCAVATED OR DREDGED			
a. Earth, straight and uniform			
1. Clean, recently completed	0.016	0.018	0.020
2. Clean, after weathering	0.018	0.022	0.025
3. Gravel, uniform section, clean	0.022	0.025	0.030
4. With short grass, few weeds	0.022	0.027	0.033
b. Earth, winding and sluggish			
1. No vegetation	0.023	0.025	0.030
2. Grass, some weeds	0.025	0.030	0.033
3. Dense weeds or aquatic plants in deep channels	0.030	0.035	0.040
4. Earth bottom and rubble sides	0.025	0.030	0.035
5. Stony bottom and weedy sides	0.025	0.035	0.045
6. Cobble bottom and clean sides	0.030	0.040	0.050
c. Dragline excavated or dredged			
1. No vegetation	0.025	0.028	0.033
2. Light brush on banks	0.035	0.050	0.060
d. Rock cuts			
1. Smooth and uniform	0.025	0.035	0.040
2. Jagged and irregular	0.035	0.040	0.050
e. Channels not maintained, weeds and brush uncut			
1. Dense weeds, high as flow depth	0.050	0.080	0.120
2. Clean bottom, brush on sides	0.040	0.050	0.080
3. Same, highest stage of flow	0.045	0.070	0.110
4. Dense brush, high stage	0.080	0.100	0.140
NATURAL STREAMS			
1. Minor streams (top width at flood stage <100 ft)			
a. Streams on Plain			
1. Clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
2. Same as above, but more stones/weeds	0.030	0.035	0.040
3. Clean, winding, some pools/shoals	0.033	0.040	0.045
4. Same as above, but some weeds/stones	0.035	0.045	0.050
5. Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
6. Same as 4, but more stones	0.045	0.050	0.060
7. Sluggish reaches, weedy, deep pools	0.050	0.070	0.080

* Rev 7/09

Appendix 7D-1 **Values of Roughness Coefficient n (Uniform Flow)**

Type of Channel and Description	Minimum	Normal	Maximum
8. Very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
b. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
1. Bottom: gravels, cobbles and few boulders	0.030	0.040	0.050
2. Bottom: cobbles with large boulders	0.040	0.050	0.070
2. Floodplains			
a. Pasture, no brush			
1. Short grass	0.025	0.030	0.035
2. High grass	0.030	0.035	0.050
b. Cultivated area			
1. No crop	0.020	0.030	0.040
2. Mature row crops	0.025	0.035	0.045
3. Mature field crops	0.030	0.040	0.050
c. Brush			
1. Scattered brush, heavy weeds	0.035	0.050	0.070
2. Light brush and trees, in winter	0.035	0.050	0.060
3. Light brush and trees, in summer	0.040	0.060	0.080
4. Medium to dense brush, in winter	0.045	0.070	0.110
5. Medium to dense brush, in summer	0.070	0.100	0.160
d. Trees			
1. Dense Willows, summer, straight	0.110	0.150	0.200
2. Cleared land with tree stumps, no sprouts	0.030	0.040	0.050
3. Same as above, but with heavy growth of sprouts	0.050	0.060	0.080
4. Heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.080	0.100	0.120
5. Same as above, but with flood stage reaching branches	0.100	0.120	0.160
3. Major Streams (top width at flood stage > 100 ft)			
The n-value is less than that for minor streams of similar description, because banks offer less effective resistance.			
a. Regular section with no boulders or brush	0.025	-	0.060
b. Irregular and rough section	0.035	-	0.100

Source: Chow, V.T., FHWA's HDS-6 publication*

* For bare earth linings when the soil classifications in accordance with either AASHTO or USCS designations are known, use the Manning's "n" values recommended in the appropriate table from Appendix 7D-2

2.2.5 Channel Velocity

The lining of open channels with drainage areas of five acres or less shall be designed to withstand the erosive effects of a 2-year storm.. The final design shall be consistent with velocity limitations for the selected channel lining, as presented in Table 2-1.

Open channels associated with dam embankment spillways or other structures where catastrophic failure could result from a lining failure may be required to be designed to withstand a more severe storm event.

Where open channels receive flow from storm drains, culverts, or other open channels, or in other areas where channel velocity may cause scouring or erosion, outlet protection or energy dissipation may be necessary to reduce the potential for severe erosion. For the design of energy dissipation devices, see Chapter 6.

Velocity calculations shall be made at the steepest section the channel.

TABLE 2-1
Maximum Velocity Based on Channel Lining

Channel Lining	Maximum Velocity (Design Storm)	
	Erosion Resistant Soils[1]	Easily Erodible Soils[2]
Vegetative Lined Channels		
Tall Fescue Grass Mixtures	5 fps	3 fps
Kentucky Bluegrass	5 fps	3 fps
Annual and Perennial Rye	4 fps	3 fps
Sod	4 fps	3 fps
Geosynthetic Lined Channels		
VDOT EC-2	4 fps	
VDOT EC-3, Type A	7 fps	
VDOT EC-3, Type B	10 fps	
Other	Per Mfr Recommendations	
Riprap	Dependent on stone size and thickness, see VDOT Drainage Manual for design of riprap	
Concrete	None	

[1] Erosion resistant soils include those with a high clay content and high plasticity, silty clay, sandy clay, and clay.
[2] Easily erodible soils include those with a high content of fine sand or silty, lower plasticity or non-plasticity, sand, silt, sandy loam, and silty loam with an erodibility factor (K) greater than 0.35.

2.2.6 Channel Slope

Generally the slope of an open channel shall be established by the site topography. Open channels must be graded to drain with no standing water following a rain event. The minimum allowable grade shall be 2 percent for vegetative lined and riprap-lined open channels and 1 percent for a concrete open channel.

The maximum allowable grade for a stormwater channel shall be dependent on the channel lining materials and its ability to withstand erosion during the design storm.

2.2.7 Cross Sectional Area

Open channel cross-sectional area shall be designed based on site restrictions and channel capacity requAcceptable cross-sectional area options include:

- Vee
- Parabolic
- Trapezoidal
- Rectangular

2.2.7.1 Vee

For design aids, see the VDOT Drainage Manual and the VA ESC Handbook.

The maximum side slope of a vee-shape open channel is 3 horizontal to 1 vertical for natural or vegetated channels and is 2 horizontal to 1 vertical for riprap, concrete or as approved by SID.

2.2.7.2 Parabolic

For design aids, see the VDOT Drainage Manual and the VA ESC Handbook.

2.2.7.3 Trapezoidal

For design aids, see the VDOT Drainage Manual and the VA ESC Handbook.

The maximum side slope of a trapezoidal-shape open channel is 3 horizontal to 1 vertical for natural or vegetated channels and is 2 horizontal to 1 vertical for all other linings engineered to be stable at this slope.

2.2.7.4 Rectangular

Rectangular channels shall only be allowed where site restrictions prevent the installation of a vee, parabolic, or trapezoidal channel.

The requirements for rectangular channels apply to any open channel with side slopes greater than 2 horizontal to 1 vertical and include the following:

- Rectangular channels must either be constructed of concrete or gabions.
- An approved safety barrier must be placed on both sides for the length of the rectangular channel, where the channel is more than 3 feet deep.
- Care must be taken to ensure that energy dissipation is placed at the outfall of the rectangular channel to prevent erosion at the discharge point.

2.2.8 Channel Lining

An open channel lining shall be designed based on the cross-section, slope, and channel velocity requirements. The design may be based on a consideration of either permissive velocity or tractive force as described in the VDOT Drainage Manual.

The preferred method for analyzing channel linings is to compare the maximum permissible velocity for the channel lining, listed in Table 2.1 in this chapter of the Design Manual, to the design velocity computed using Manning's equation to verify the selected lining is adequate. As an alternative, the selected lining may be analyzed using the Tractive Force Method in the VDOT Drainage Manual. This method analyzes critical shear loading on the open channel bottom and side slopes. The permissible tractive force for various soils is located in the Appendix of the VDOT Drainage Manual.

Open channels may have different lining materials in different channel reaches based on velocity and potential erosion conditions. Care must be exercised to avoid erosion at open channel transition points.

The open channel lining will have an impact on the design capacity in the form of the roughness coefficient. Allowable open channel linings include the following:

2.2.8.1 Natural

To the extent possible, natural channels shall be preserved.

To determine the permissible velocities in natural channels, based on soil conditions, use permissible velocities based on soil conditions published in the VDOT Drainage Manual. If the design storm velocity exceeds the permissible velocity, a natural channel cannot convey the stormwater runoff without modifying the discharge flow conditions or improving the natural channel.

2.2.8.2 Vegetative-Lined

Vegetated or grass-lined channels include man-made channels lined with established vegetation. These channels usually include a geosynthetic mat for channel stabilization for design flow velocities.

The type of grass allowable for vegetative-lined open channels is dependent on the slope of the channel and the peak calculated velocity. Table 2-1 details the maximum permissible velocities for various channel linings.

A permanent channel stabilization geosynthetic mat should be considered for all vegetated channels. There is a wide variety of geosynthetic stabilization mat options from various manufacturers. The geosynthetic mat selected should be adequate for the slope and design flow velocities calculated for the channel. Where appropriate, VDOT Road and Bridge Standard EC-2 or EC-3 may be used.

Where a permanent geosynthetic mat is used to provide channel stabilization, information on the proposed mat, in the form of the manufacturer's catalog information, shall be submitted as a part of the stormwater management plan. The catalog information shall include the manufacturer's recommendations for maximum allowable velocity. Design drawings must state that the geosynthetic stabilization mat shall be installed in strict accordance with the manufacturer's recommendations.

Where a permanent channel stabilization geosynthetic is not used, a temporary geosynthetic lining designed to provide a measure of the bed/bottom and bank stability until such time as a reasonably stable and mature stand of vegetation is established shall be provided.

2.2.8.3 Riprap-Lined

The use of vegetated and geosynthetic-lined open channels for mild-sloped open channels and concrete for steep-sloped open channels is encouraged. Riprap-lined channels will not be acceptable where vegetated or geosynthetic-lined open channels are feasible. However, where design flow velocities exceed the erosive capability of a natural or vegetative-lined channel, riprap may be used as a channel lining in areas where erosion is a concern. For an extended length of high velocity channel, consideration should be given to using a concrete channel rather than riprap.

Use of riprap-lined channels requires pre-approval from SID.

Where riprap is approved by SID, it shall meet VESCH Specification 3.19, VDOT Standards, and VDOT Specifications.

2.2.8.4 Concrete-Lined

Concrete shall be considered where design velocities dictate or where there is a need to provide the maximum level of erosion protection.

2.2.9 Freeboard Requirements

Open channels shall have a minimum of 6" of freeboard above the calculated water surface elevation for the design peak flow, unless the flow is supercritical. Where the flow is supercritical, a minimum of 12" of freeboard is required. Flow is supercritical when:

$$V / (32.2 \times H)^{0.5} > 1$$

Where:

V =Velocity (fps)
H =Depth of flow (feet)

At channel bends and curves, the freeboard shall be measured from the calculated water surface elevation, including the increased depth due to the superelevation of the water surface.

2.2.10 Calculation of Depth of Flow at Bends and Curves

Increases in the depth of flow occur at bends and curves due to the superelevation of the water surface. Superelevation of the water surface at bends and curves is calculated, using the VDOT Drainage Manual, by:

$\Delta Z = V^2 / (32.2 \times r_c) \times (r_o - r_i)$

Where:

ΔZ =Difference in water surface elevation between the concave and convex banks (ft)
V =Average velocity (ft/s)
r_c =Radius of the center of the stream at the bend (ft)
r_o =Radius of the outside bank of the stream at the bend (ft)
r_i =Radius of the inside bank of the stream at the bend (ft)

The increase in the normal stream flow depth at the outer bank of an open channel bend is one half of ΔZ.

2.2.11 Environmental Considerations and Aquatic Organism Protection

Construction or modifications to open channels shall comply with all applicable laws and regulations. The applicant is responsible for procuring all necessary permits, such as USACE and DEQ Wetland Permits, DEQ VPDES Permits, etc., prior to obtaining SID approval.

2.2.12 Maintenance Requirements

The Operator is responsible for maintenance of open channels until the termination of land disturbance as described in the Annual Standards and Specifications. Maintenance includes periodically pruning or mowing vegetation and removing debris.

No one shall fill, modify, or construct structural modifications that impair or restrict flow in open channels.

3.0 CULVERTS

A culvert is a single run of storm drain pipe that conveys water or stormwater under a road, railway, embankment, sidewalk, or other open channel obstruction. A culvert typically connects two open channels, but it may connect an open channel to a storm drain.

Proper culvert design must consider many factors including:

- Design Flow
- Inlet conditions (flow approach conditions, allowable headwater, culvert inlet configuration)
- Culvert conditions (pipe roughness, pipe slope, diameter and length)
- Tailwater depth
- Buoyancy potential
- Environmental considerations and effects on aquatic life
- Design loads and service life of the pipe material

Refer to the VDOT Drainage Manual for a more thorough discussion of these items. For the design of stormwater inlets and storm drains, see Chapter 4.

3.1 References

Except where more stringent requirements are presented in this Design Manual, culverts shall comply with VDOT requirements. The primary design reference is the VDOT Drainage Manual. Other appropriate references include the latest editions of the following:

- VDOT Road and Bridge Standards
- VDOT Road and Bridge Specifications
- VA ESC Handbook
- VDOT Instructional and Informational Memorandum IIM-LD-121.15, Allowable Pipe Criteria for Culverts and Storm Sewers
- FHWA Hydraulic Design of Highway Culverts HDS No. 5, Pub. No. FHWA- HIF-12-026
- FHWA Debris Control Structures Evaluation and Countermeasures HEC No. 9, Pub. No. FHWA-IF-04-016
- FHWA Culvert Design for Aquatic Organism Passage HEC No. 2, Pub. No. FHWA-HIF-11-008

3.2 Design Methodology and Criteria

3.2.1 Computational Methods

Computations may be manual or by computer program.

Manual computations use design equations and nomographs. Results are documented on VDOT's Design Form LD-269.

There are a number of computer programs available to design culverts. Any of these computer programs will be acceptable if their methodologies are based on the same equations and nomographs accepted by VDOT, and if they provide the same documentation of inputs, assumptions, and output as are contained on VDOT's Design Form LD-269.

3.2.2 Hydrology

3.2.2.1 Design Flow Methodology

See Chapter 1 for methodology used to determine design flows. Generally culverts shall be designed based on the peak flow (steady state), ignoring the effects of temporary upstream storage.

3.2.3 Culvert Hydraulics

3.2.3.1 Design Flow

Culverts shall be designed in accordance with the VDOT Drainage Manual, latest edition.

Compliance with the National Flood Insurance Program (NFIP) is necessary for all locations where construction will encroach on a 100-year floodplain. The Town of Blacksburg administers the NFIP on the Virginia Tech main campus, in accordance with Executive Memorandum 2-97.

In addition, the 100-year peak flow (without the addition of the obstruction allowance) shall be routed through all culverts, determining the headwater depth behind the culvert with road overtopping, to ensure that buildings and other structures are not flooded and that adjacent roadways and adjacent properties do not suffer significantly increased damage during the 100- year storm event. Storage impacts of water behind the culvert may be considered in the calculation but is not required.

3.2.3.2 Allowable Headwater

The allowable headwater is the depth of water that can be ponded at the upstream end of the culvert during the design condition, as measured from the culvert inlet invert.

The allowable headwater depth shall be limited by the following conditions:

- Headwater does not cause upstream property damage;
- Headwater does not increase the 100-year flood elevation, as mapped by NFIP;
- During a design storm event, the water surface shall be a minimum of 18 inches below the shoulder of the road at the point where the culvert crosses, or the low point of the road grade where the water would overtop the road;
- Headwater depth shall not exceed 1.5 times the diameter or height of the culvert barrel;
- Headwater depth shall not be such that stormwater flows to other ditches or terrain, which permit the flow to divert around the culvert.
- In most instances, the roadway overtopping may be treated as a broad crested weir.
- The maximum overtopping depths during a 100-year storm event for various street classifications are as follows:

Classification	Max. Depth at Crown	Max. Velocity
Local/Collector	1 ft*	6 fps
Arterial/Highway	No Overflow	No Overflow

3.2.3.3 Tailwater Conditions

Tailwater is the water into which a culvert outfall discharges. Culvert design shall be based on tailwater conditions that could reasonably be anticipated during the design condition.

- If an upstream culvert outlet is located near a downstream culvert inlet, the headwater elevation of the downstream culvert may establish the design tailwater depth at the upstream culvert.
- If the culvert discharges into a lake, pond, stream, or other body of water, the maximum water elevation of the body of water during the design storm may establish the design tailwater elevation at the upstream culvert.

3.2.3.4 Inlet and Outlet Control

Culvert hydraulic design shall consider both inlet and outlet control conditions. For a culvert operating under inlet control, the headwater elevation is governed by the inlet geometry. For an outlet control culvert, the inlet geometry, barrel characteristics and tailwater elevation all impact the headwater elevation.

Minimum culvert performance is determined by analyzing both inlet and outlet control for a given flow and using the highest resulting headwater.

Inlet Control

The following factors are considered when calculating inlet control headwater:

- Inlet Area – cross sectional area of the culvert entrance face
- Inlet Edge – projecting, mitered, headwall, or beveled edges are common
- Inlet Shape – rectangular, circular, elliptical, or arch are common

Nomographs for calculating headwater and flow capacity are found in the VDOT Drainage Manual.

Outlet Control

The following factors are considered when calculating outlet control headwater:

- Manning's Roughness (n) – based on barrel material
- Barrel Area – cross section perpendicular to the flow
- Barrel Length
- Barrel Slope

- Tailwater Elevation

Outlet control affects the hydraulic grade line of the flow through the culvert. To calculate the hydraulic grade line, reference the equations for velocity, velocity head, entrance losses, friction losses, and exit losses contained in the VDOT Drainage Manual.

For nomographs, cross sections, and pipe materials, see the VDOT Drainage Manual.

3.2.3.5 Culvert Velocity

Outlet velocity must be checked to assure that excessive erosion and scour problems will not occur.

Culvert outlet protection shall be provided in accordance with the standards and specifications for Outlet Protection and Riprap in the VA ESC Handbook.

Culverts under roadways shall be provided with end sections or endwalls in accordance with the outlet protection requirements of the VDOT Drainage Manual.

Where a special design is needed to reduce outlet velocity, it shall be designed in accordance with VDOT standards.

The minimum velocity in a culvert barrel must be adequate to prevent siltation at low flow rates. At a minimum this velocity shall be 3 feet per second for a 2-year storm event.

3.2.4 Structural Design

All culverts shall be designed to withstand a HS-20 highway loading, unless it crosses under a railroad, in which case the culvert shall be designed for railroad loads. The structural design shall consider the depth of cover, trench width and condition, bedding type, backfill material, and compaction.

3.2.5 Materials

Culverts in public easements or rights-of-way shall be constructed of materials based on the following:

- Culverts under a roadway in the right-of-way shall be VDOT approved materials.
- Culverts under sidewalks, trails, etc. shall be reinforced concrete pipe (RCP) or HDPE.

3.2.6 Culvert Sizes

The minimum culvert size shall be 18-inch diameter.

Culverts shall meet all cover conditions required. Where the site conditions preclude the use of a single culvert barrel to meet the design flow conditions, multiple barrel culverts are acceptable.

The maximum length of a culvert shall be 300 feet. A culvert longer than 300 feet shall have manholes or junction boxes and shall fall under the requirements of Chapter 4.

3.2.7 End Conditions

Headwalls and end sections shall normally be required on inlets and outlets, as described below.

3.2.7.1 Prefabricated End Sections

Prefabricated end sections, or flared end sections, provide for a better flow path, improving the design flow and headwater conditions.

Prefabricated end sections shall be provided for culverts 18-inch to 36-inch diameter, except:

- Where culvert alignment exceeds 20 feet in vertical elevation change or culvert slope exceeds a 2:1 slope, a standard concrete headwall shall be provided instead of a prefabricated end section.
- Where a concrete headwall is provided.

3.2.7.2 Concrete Headwalls and Structures

Precast concrete headwalls shall be provided at all culvert inlets and outlets, unless other end conditions are allowed, as stated above. Precast concrete headwalls shall meet the requirements of the VDOT Road and Bridge Standards and VDOT Road and Bridge Specifications.

Wingwalls may be required in conjunction with headwalls. Culvert pipes 48" or larger in diameter shall have concrete wingwalls. Wingwalls are generally used where the culvert is skewed to the normal channel flow or where the side slopes of the channel or roadway are unstable. Wingwalls shall meet the requirements of the VDOT Standards and VDOT Specifications. Wingwalls shall be set at an angle between 30 degrees and 60 degrees from the headwall.

Concrete aprons may be used at the entrance or the exit of a culvert. Aprons are typically used where high velocities or headwater conditions may cause erosion upstream or downstream of the culvert. An apron shall not protrude above the normal stream bed elevation.

Special design concrete slab end treatment, per VDOT Standards, may be used as a concrete end section.

3.2.8 Multiple Barrel Culverts

Multiple barrel culverts shall be allowed where single culverts cannot handle the design flow while meeting the required cover or headwater condition requirements. The design of multiple barrels should avoid the need for excessive widening of the upstream or downstream receiving channels.

The minimum spacing between culverts in a multiple barrel culvert design shall be that required to provide adequate lateral support and allow proper compaction of bedding material under the pipe haunches.

3.2.9 Culvert Skew

Where possible, culverts shall be installed parallel to the flow path. The maximum allowable skew shall be 45 degrees as measured from the line perpendicular to the roadway centerline.

3.2.10 Buoyancy

Verify that the culvert pipe, end sections, and concrete endwall structures will not fail under hydrostatic uplift conditions.

The buoyancy force consists of the weight of water displaced by the pipe and the fill material that is over the pipe (below the headwater depth). The force resisting buoyancy includes the weight of the pipe, weight of the water within the pipe, and the weight of fill material over the pipe.

Buoyancy is more likely to be a problem where:

- Lightweight pipe is used
- The pipe is on a steep slope (usually inlet control with the pipe flowing partially full)
- There is little weight on the end of the pipe (flat embankment slopes, minimum cover, and/or no endwalls)
- High headwater depths (HW/D>1.0)

Suitable cover, footings, or anchor blocks may be required to ensure the culvert's integrity during design conditions.

3.2.11 Debris and Trash Racks

In general, trash racks or debris deflectors shall not be used where other site modifications may be made to prevent excessive trash or debris from entering the culvert. However, they may be required at specific locations by SID where large amounts of storm debris may be anticipated.

3.3 Installation

All culvert pipe, headwalls, end sections, outlets, and other peripheral structures shall be installed in accordance with VDOT requirements and the manufacturer's recommendations. The characteristics of the trench, bedding, and pipe material all impact the structural strength of the pipe system. The installed culvert conditions shall comply with the design assumptions and calculations.

3.3.1 Bedding Material

Bedding material and installation shall comply with the requirements of the VDOT Specifications.

3.3.2 Backfill

Backfill shall be suitable material and shall be placed and compacted in accordance with VDOT Specifications.

A minimum of 12" of backfill shall be placed over the top of a HDPE or CMP culvert prior to placing pavement or other surface treatment.

3.4 Environmental Considerations and Aquatic Organism Protection

Where compatible with good hydraulic engineering, a culvert shall be located in "dry" conditions. Where this is not possible, the culvert shall be located to minimize impacts to streams or wetlands.

When a culvert is set in a perennial stream, the invert of the culvert shall be set below the normal flow line of the stream as required in the VDOT Drainage Manual. The grade of the culvert shall not exceed the grade of the natural stream in that section.

Where construction requires environmental permits, the applicant shall be responsible for obtaining all necessary environmental permits and complying with their requirements.

3.5 Maintenance Requirements

The Operator is responsible for maintenance of culverts until the termination of land disturbance as described in the Annual Standards and Specifications.

4.0 STORM DRAINS

A storm drainage system consists of two or more interconnected pipes and one or more structures designed to intercept and convey stormwater runoff from specific storm event without surcharge. Storm drains collect and transport stormwater from a site primarily through the use of a closed pipe network. For the stormwater to be efficiently handled in a storm drain, the site must also have an efficient way to collect stormwater runoff and have it enter into the piped network. Once in the storm drain, the stormwater is routed to a discharge outfall.

Storm drainage systems include:

- Inlets
- Storm drain piping and structures that convey stormwater runoff to the outfall

This section defines criteria and restrictions that shall be used in designing and constructing storm drains. See the VDOT Drainage Manual for more in-depth information.

Profiles for all storm drains 12 inches in diameter and greater shall be provided on the site plans.

4.1 References

Except where more stringent requirements are presented in this Manual, storm drainage systems shall comply with VDOT and DEQ requirements. The primary design reference is the VDOT Drainage Manual. Other appropriate references include:

- VDOT Standards
- VDOT Road and Bridge Specifications
- VA ESC Handbook

4.2 Design Methodology and Criteria

4.2.1 Computational Methods

Computations may be manual or by computer program.

Manual computations use design equations and nomographs. Results may be documented on VDOT work sheets.

- Form LD-204 Stormwater Inlet Computations
- Form LD-229 Storm Drain Design Computations
- Form LD-347 Hydraulic Grade Line Computations

There are a number of computer programs available to design storm drainage systems. Any of these computer programs will be acceptable if their methodologies are based on the same equations and nomographs accepted by VDOT, and if they provide the same documentation of inputs, assumptions, and output as are contained on VDOT's work sheets.

Computational methods are explained in detail, including comprehensive design examples, in the VDOT Drainage Manual.

4.2.2 Hydrology

See Chapter 1 for the methodology used to determine design flows. Calculations establishing the design flow shall be submitted with the Stormwater Management Plan. Design flows shall be based on the ultimate build-out of the project, or of the campus precinct in accordance with the Virginia Tech Stormwater Management Master Plan.

4.2.3 Design Flows

Inlets shall be designed for 10-yr storm frequencies and intensities consistent with the VDOT Drainage Manual.

Storm drains shall be designed in accordance with Chapter 1 of this manual.

4.2.4 Measures to Convey Stormwater Runoff to Inlets

4.2.4.1 Curb and Gutter

Curb and gutter at the edge of pavements may be used to collect stormwater runoff from roadways. Curbing captures stormwater runoff and directs it to stormwater collection inlets while protecting adjacent properties from flooding and erosion due to sheet flow runoff from the impervious roadways.

A curb and gutter forms a triangular conveyance channel. When a storm occurs, the runoff from the road creates a spread of water from the curb. The curb and gutter must be designed to convey this flow and with associated drainage structures prevent the spread onto the roadway from impacting traffic. The spread width of flow is determined by using nomographs. For curb and gutter flow, a Manning’s n value of 0.015 is used in the computational analysis.

Curb and gutter dimensions and design shall meet VDOT Standards.

4.2.4.2 Open Channels

Open channels may be used to collect site drainage and convey it to a storm drain inlet. Design requirements for open channels are covered in Chapter 2.

4.2.5 Storm Drain Inlets

4.2.5.1 General

Storm drain inlets are used to collect stormwater runoff from roads, sidewalks, or low elevations during storm events and provide a method for conveying the stormwater into the storm drain system. This is usually accomplished by placing storm drain inlets at regular intervals or at key locations to intercept flows and control the stormwater spread width. The design criteria for limiting the spread of water on travel lanes is found in the VDOT Drainage Manual.

There are several different types of storm drain inlets that can be used to meet this purpose, and the designer shall choose the proper inlet structure based upon site conditions and design conditions to maximize the drainage efficiencies.

- Curb
- Grate
- Slotted Drain/Trench
- Combination

Stormwater management plans shall include a contour plan with sufficient contours shown to ensure positive drainage to an inlet. Inlet Volume Capacity Calculations are required with the Stormwater Management Plan submittal.

4.2.6 Storm Drain Inlets

4.2.6.1 Curb Inlets

Curb inlets are vertical openings in the curb covered by a top slab. These inlets can convey large quantities of water, but also allow for large amounts of debris to enter the storm drain system.

Curb inlets shall be used to the maximum extent possible for pavement drainage.

4.2.6.2 Grate Inlets

Grate inlets are horizontal grates that are usually used in depressed medians or in other areas of low elevations. Grate inlets are often referred to as drop inlets or DIs. Grate inlets shall be pedestrian rated when installed in paved areas. Where they are used in pavement, inlet grates shall be bicycle safe.

4.2.6.3 Combination Inlets

Combination inlets combine both the vertical opening used by curb inlets and the horizontal grate used by grate inlets. These inlets are often used when the inlet chamber is required to be under the gutter or street pavement away from the sidewalk or other utilities. Combination inlets shall be avoided where possible. Where they are used, they must have bicycle-safe grates.

4.2.6.4 Trench Drain Inlets

Trench drain inlets are cast-in-place or precast concrete trenches covered by a grate that are used to intercept sheet flow.

4.2.6.5 Inlet Locations

Inlets shall be located to meet the design requirements of the VDOT Drainage Manual for maximum spread width. In addition, inlets shall be provided, regardless of contributing drainage area, as follows:

- At sag points in the gutter grade.
- Either side of sag point inlet (flanking inlets).
- Upstream of median breaks, crosswalks, and street intersections.

- Immediately upstream and downstream of bridges.
- On side streets at intersections, where flow is approaching the main line.
- Behind curbs, shoulders, or sidewalks to drain low areas or intercept concentrated flow.
- At 1% cross slope upstream of cross slope reversals.
- At any low elevation in the grade.

Inlets installed in pathways likely to be used by pedestrians or bicyclists shall be a pedestrian rated grate.

4.2.6.6 Access

All inlets shall have a removable grate or manhole cover to allow access for clean out.

4.2.6.7 Inlet Capacities

The capacities of each inlet type are contained in the VDOT Drainage Manual. Capacities are determined from equations or nomographs that are contained within the VDOT Drainage Manual. Documentation of inlet capacity shall be made on VDOT Form LD-204, Stormwater Inlet Computations or computer modeling output.

4.2.6.8 Separation of Pipes

Where two or more storm drains enter a concrete structure at or near the same elevation, a 6" minimum horizontal clearance must be maintained between the pipes. Additional clearance between pipes shall be provided if required to protect the structural integrity of the structure.

4.2.7 Storm Drain Pipes

4.2.7.1 Flow Capacity

Based on the size and slope of the storm drain, the design capacity for a pipe flowing full can be determined using Manning's equation.

$$Q = A \times 1.49/n \times R^{2/3} \times S^{1/2}$$

Where:

Q =Flow in the pipe (cfs)
A =Cross-sectional Area of the pipe (ft^2)
R =Hydraulic radius; for circular pipe flowing full, R=Diameter/4 (ft)
S =Storm drain slope (ft/ft)
n =Pipe roughness coefficient

The design flow capacity of a storm drain shall comply with the design frequencies set forth in the VDOT Drainage Manual. In a roadway underpass, or depressed section, where ponded water can only be removed through the storm drain system, a 100-year frequency storm event shall be used to design the storm drain at the sag point.

4.2.7.2 Storm Drain Slope

To deter the settling of debris and sediment in the storm drain pipe, the pipe shall be designed to ensure positive slope and maintain a minimum velocity of 3 feet per second during a 2-year frequency storm.

The maximum pipe velocity in any storm drain shall be 20 feet per second during a 10-year frequency storm to prevent excessive abrasion of the pipe and erosion at the discharge. If the pipe velocity exceeds 15 feet per second during a 10-year frequency storm, a reinforced concrete storm drain pipe is required.

Storm drains shall be sloped to meet the velocity requirement set in this chapter. Slopes greater than 16 percent shall be avoided if possible. If unavoidable, drop structures shall be utilized in steeper terrain. In addition, storm drains with slopes steeper than 16% must have anchor blocks for support.

4.2.7.3 Pipe Size

The minimum recommended conduit size for storm drainage pipe is 15-inch diameter or its equivalent for non-circular shapes. Where necessary, it will be permissible to use a 12-inch diameter pipe for laterals or initial pipe runs of 50 feet or less. Pipe size shall not be reduced along the direction of the flow, except as required for proper operation of stormwater management facilities.

4.2.7.4 Access

Regardless of pipe size, a cleanout access point, either an inlet, manhole, or junction box shall be provided at a maximum of every 300 feet of pipe.

4.2.7.5 Water-Tight Joints

The use of water-tight joints is encouraged to prevent infiltration of groundwater, and potential pollutants carried by contaminated groundwater, and to prevent settlement problems from occurring due to soil materials washing into storm drains.

SID reserves the right to require the use of water-tight joints in the following locations:

- Culverts and storm drains under pavement, sidewalks, or concrete structures
- Through stormwater "hotspots"
- In areas where groundwater may be contaminated by pollutants
- On steep slopes
- Culverts

The following land uses and activities are designated as stormwater hotspots:

1) Vehicle salvage yards and recycling facilities
2) Vehicle fueling stations
3) Vehicle service and maintenance facilities

4) Vehicle and equipment cleaning facilities
5) Fleet storage areas (bus, truck, etc.)
6) Industrial sites (for SIC codes contact VA DEQ)
7) Marinas (service and maintenance areas)
8) Outdoor liquid container storage
9) Outdoor loading and unloading facilities
10) Public works storage areas
11) Facilities that generate or store hazardous materials
12) Commercial container nursery
13) Golf courses
14) Chemical storage
15) Dry cleaning operations

4.2.8 Determination of Hydraulic Grade Line

4.2.8.1 General

The hydraulic grade line represents the free water surface elevation of water in a pipe system. Where the hydraulic grade line is above the top of a pipe, the pipe is flowing under pressure. The hydraulic grade line in a manhole or other structure is the elevation to which water will rise.

Hydraulic grade lines shall be calculated and evaluated for all storm drains. The hydraulic grade line shall be calculated using VDOT methods and equations that are fully described in the VDOT Drainage Manual. Calculations shall be documented on VDOT Form LD-347, Hydraulic Grade Line Computations, or computer modelling output. The output shall be in the form of profiles showing the HGL in relation to the pipe and structures.

The hydraulic grade line shall not exceed any critical elevation during the design storm. Critical elevations include rising above the ground elevation at inlets or other structures, or reaching an elevation where storm flow could back up to cause flooding damage.

The calculation of the hydraulic grade line begins at the system outfall and proceeds upstream to each structure in the system. The calculation is based on the principal of conservation of energy as shown below and includes major and minor energy losses:

$$HGL_{us} = HGL_{ds} + H_f + H_m$$

Where:

HGL_{us} = Elevation of hydraulic grade line at the upstream structure
HGL_{ds} = Elevation of hydraulic grade line at the downstream structure
H_f = Pipe friction loss
H_m = Summation of minor head losses (junctions, bends, etc.)

Major head losses are attributable to friction losses within the pipe. Minor head losses include losses from:

- Junctions
- Exits
- Entrances
- Bends in Pipes
- Access holes
- Conflict pipes
- Plunging flow
- Expansions and contractions
- Appurtenances such as weirs, diverters, valves and meters

- Outfall Conditions

The hydraulic grade line starts at the system outfall. At this point the hydraulic grade line shall be the actual tailwater elevation or the elevation of 0.8 times the diameter of the outlet pipe, whichever is higher. If the system discharges into a detention or retention pond, the hydraulic grade shall start at the 10-year water surface elevation.

- Pipe Friction Losses

The friction slope is the energy slope for that run of pipe. The friction slope is determined by inserting pipe information and design flow into Manning's equation and solving for S (slope). The total friction head loss in the run of pipe is the friction slope multiplied by the length of the run.

Where the hydraulic grade line falls below the crown of the pipe, the elevation of normal flow is the hydraulic grade line.

- Junction Losses

General

Junction head losses are the summation of entrance (H_i), exit (H_o), and bend losses (H_Δ). When calculating junction losses it is important to use actual flow velocities. If pipes are flowing partially full, then partially full velocities are used.

Entrance (Expansion) Losses

Entrance loss at a junction is given by:

$H_i = K_e (V_i^2 / 2g)$

Where:

H_i = Entrance head loss
K_e = Entrance loss coefficient. K_e = 0.35
v_i= Velocity in the inlet pipe. Where more than one inlet pipe is present, use the velocity from the pipe that has the greatest momentum (Q*V)
g = Gravitational acceleration constant, 32.2 ft/s^2

Exit (Contraction) Losses

Exit loss at a junction is given by:

$$H_o = K_o(V_o^2 / 2g)$$

Where:

H_o = Exit head loss
K_o = Exit loss coefficient. K_o = 0.25, except that K_o = 0.3 when computing the loss leaving the initial inlet
V_o = Velocity in the outlet pipe
g = Gravitational acceleration constant, 32.2 ft/s^2

Bend Losses

Bend losses at a junction are dependent on the angle between the inlet and outlet pipes. If the inlet and outlet pipe are in line with one another (no bend), the angle is 0 degrees and there is no bend loss. As the angle increases towards 90 degrees, the bend loss increases. Storm drain systems should not be designed with bend angles greater than 90 degrees. Where more than one pipe enters a junction at an angle, the H_Δ should be figured on all bends and the largest one used as the bend loss. The bend loss is given by:

$$H_\Delta = K (V_i^2 / 2g)$$

Where:

H_Δ = Head loss at bend
K = Bend loss coefficient. K is determined by consulting Figure 9-9 in the VDOT Drainage Manual.
V_i = Velocity in the inlet pipe.
g = Gravitational acceleration constant, 32.2 ft/s^2

Plunging Losses

Where surface inlet inflow is 20 percent or more of the total flow through a junction, or when a lateral pipe enters a junction with its invert elevation above the crown of the outgoing pipe and the flow in the lateral pipe is 20 percent or more of the total flow through the junction, the total head loss from the structure ($H_i + H_o + H_\Delta$) shall be multiplied by 1.3 (increased by 30 percent). This adjustment is cumulative with the adjustment for plunging losses.

Inlet Shaping

Inlet shaping refers to how the invert is shaped to provide smooth flow through the structure and is required in all manholes and inlets. When VDOT Standard IS-1, inlet shaping, is used in a structure, the total head loss from the structure (H_i + Ho + HΔ) shall be multiplied by 0.5 (decreased by 50 percent). This adjustment is cumulative with the adjustment for inlet shaping.

4.2.9 100-Year Conditions

Where there is the possibility of building structures flooding, conditions during the 100-year storm shall be analyzed to verify that all existing and proposed structures do not flood. Flow from the 100-year storm may be carried overland as well as by the storm drain system.

4.2.10 Materials

4.2.10.1 Structures

All stormwater structures (inlets, manholes, and junction boxes) located in public easements or rights-of-way shall be precast or cast-in-place concrete. All structures, frames, grates, and covers shall be in accordance with VDOT Standards and VDOT Specifications.

4.2.10.2 Storm Drain Pipe

Storm drain pipe in roadways shall be constructed of Reinforced Concrete Pipe (RCP). Storm drain pipe in sidewalks, trails, etc shall be constructed of Reinforced Concrete Pipe (RCP) or High Density Polyethylene (HDPE). Corrugated Metal Pipe (CMP) shall not be allowed.

4.2.11 Structural Design

All inlet structures, frames and grates; and pipes shall be designed to withstand a HS-20 loading, unless a pipe crosses a railroad, in which case the pipe shall be designed for railroad loads. The structural design shall consider the depth of cover, trench width and condition, bedding type, backfill material, and compaction.

4.3 Installation

All inlets, pipes, and associated structures shall be installed in accordance with VDOT Specifications and the manufacturer's recommendations. The characteristics of the trench, bedding, and pipe material all impact the structural strength of the pipe system. The installed pipe conditions shall comply with the design assumptions and calculations.

4.3.1 Bedding Material

Bedding material and installation shall comply with the requirements of the VDOT Specifications.

4.3.2 Backfill

Backfill shall be suitable material and shall be placed and compacted in accordance with the VDOT Specifications.

Before passage of equipment, a minimum of 12" cover shall be placed over the top of a storm drain pipe prior to placement of pavement or other surface treatment. Additional depth of cover shall be provided if recommended by the manufacturer.

4.3.3 Separation of Utilities

Where storm drains cross other utilities, at least 1 foot of vertical separation shall be provided. Where 1 foot of vertical separation cannot be provided, special provisions shall be made in the bedding and backfill to avoid settlement that could cause point loadings on the storm drain or other utility.

Waterlines and sewer lines shall not pass through a storm drain inlet or manhole.

4.4 Environmental Impacts

Construction or modifications to storm drains shall comply with all applicable laws and regulations. The applicant is responsible for procuring all necessary permits.

4.5 Erosion Protection at Outfalls

Erosion protection at storm drain outlets shall be provided in accordance with the outlet protection standards contained in the VA ESC Handbook and the VDOT Drainage Manual.

4.6 Maintenance Requirements

The Operator is responsible for maintenance of storm drains until the termination of land disturbance as described in the Annual Standards and Specifications.

5.0 STORMWATER DETENTION

Stormwater detention facilities are a means of attenuating increases in peak flow rates caused by land development. In addition to providing flood control, stormwater detention facilities can protect downstream channels from increases in erosion and may provide a measure of water quality treatment. This chapter addresses general requirements for detention facilities as they relate to attenuating peak flow rates.

When a storm event occurs, stormwater runoff enters the detention facility. The outlet structure allows a portion of the stormwater runoff to discharge from the facility, while the remainder of the stormwater runoff is temporarily stored. After the end of the storm, water continues to discharge from the facility until it is empty or the permanent pool elevation is reached.

Stormwater detention facilities, as listed in VA Stormwater BMP Clearinghouse and DEQ Stormwater Regulations, include:

- Part IIB
  - Bioretention (Including Urban Bioretention)
  - Constructed Wetlands
  - Wet Ponds
  - Extended Detention Ponds
  - Underground Detention Facilities
- State Existing Facilities (Under Part IIC)
  - Detention Pond
  - Enhanced Extended Detention Pond

An underground detention facility consists of pipes or manufactured underground chambers used to temporarily store stormwater runoff following a storm event, discharging it at a controlled rate through a hydraulic outlet structure to a downstream conveyance system. An underground detention facility is dry during non-rainfall periods.

In addition to detention, the design requirements specified by this chapter shall apply to ponds created as amenities, research ponds, and farm ponds.

5.1 References

Except where more stringent requirements are presented in this Manual, the design and construction of stormwater detention facilities shall comply with VDOT and DEQ requirements. The primary design references are:

- VA SWM Handbook
- VDOT Drainage Manual
- VA ESC Handbook
- VDOT Standards

- VA Stormwater BMP Clearinghouse

5.2 Design Methodology and Criteria

5.2.1 Hydrology

See Chapter 1 for methodology used to determine design flows.

5.2.2 Design Flows and Storage Volumes

To properly design stormwater detention facilities, a flow routing program shall be used with an appropriate elevation-storage-discharge relationship for the design storm events.

5.2.3 Detention Facility Locations

Stormwater detention facilities should not be constructed within a Federal Emergency Management Agency (FEMA) designated 100-year floodplain. If this is unavoidable, the facility shall comply with all applicable regulations under the National Flood Insurance Program, 44 CFR Part 59.

The following factors shall be addressed when siting a stormwater detention facility:

- Geotechnical conditions, including soil conditions
- Karst topography
- Groundwater levels
- Existing and proposed utilities
- Aesthetic impacts on surrounding properties
- Environmental impacts, including wetlands

Stormwater basins shall be located to minimize the aesthetic impacts to adjacent properties. Basins shall be set back from property lines a distance equal to the minimum width of the applicable required Source.

Locate stormwater detention facilities to avoid collecting significant amounts of drainage from offsite areas.

All stormwater management basins shall be lined with either a clay liner or an impermeable High Density Polyethylene (HDPE) liner.

Stormwater basins shall be set back in accordance with VA Stormwater BMP Clearinghouse Specification No. 15.

5.2.4 Detention Basin Grading

Stormwater basins shall be graded to blend into the surrounding topography with the following conditions:

- Basin side slopes shall be no steeper than 3H:1V.
- Provisions shall be made for the long-term maintenance of basin slopes and periodic access for maintenance of the outlet structure and emergency spillway and removal of accumulated sediment and debris.

- The maximum allowable depth of a stormwater detention basin shall be 15 feet, as measured from the top of the embankment to the lowest point in the basin.
- The bottom of the basin shall be designed so that the entire bottom of the Extended Detention Basin is sloped at 1% to facilitate positive drainage to the outlet structure.

In addition to the above requirements, the following standards of practice should be used when designing a stormwater basin, to the extent possible:

- In order to prevent short-circuiting of a stormwater basin's storage areas, the length-to-width ratio of the basin should be a minimum of 2:1, with the flow entering the basin as far from the outlet structure as possible. A 3:1 ratio is desired where possible.
- To minimize cut and fill, the long dimension of a stormwater basin should run parallel to the contours.

5.2.5 Embankments and Emergency Spillways

Embankments and emergency spillways shall be designed in accordance with the Earthen Embankment and Vegetated Emergency Spillway specifications on the VA Stormwater BMP Clearinghouse website. A geotechnical study for the embankment and basin is required.

5.2.6 Outlet Structures and Release Rates

5.2.6.1 Stormwater Release Rates

Stormwater detention facilities shall be designed with an outlet structure to control the release rate of stormwater being held in the facility. Design release rates shall meet the requirements set forth in Chapter 5.

Research ponds, farm ponds and ponds created as amenities shall be exempt from release rate requirements.

5.2.6.2 Outlet Structure Criteria

Outlet structures generally include a principal spillway and an emergency spillway. An outlet structure may take the form of combinations of risers, pipes, weirs, or orifices. The principal spillway is intended to release flow from the design storm events at the necessary controlled rate, without allowing flow to enter the emergency spillway. The sizing of the outlet structure shall be based on the results of the hydrologic routing calculations or model. Due to the tendency of clogging, the minimum orifice diameter shall be 3 inches. A basin drain shall be installed to allow for dewatering.

Outlets from stormwater detention facilities shall be designed to function without manual, electrical, or mechanical controls.

Where necessary, energy dissipaters shall be placed at the outfall to provide a non-erosive velocity from the facility to a channel. See Chapter 6 for the design of outfall protection.

Where a stormwater basin with an earthen embankment does not have an emergency spillway, the principal spillway shall be sized to safely pass the flow from the 100-year storm without overtopping the embankment. In addition, the minimum size of the primary spillway shall be 24 inches.

Freeboard for detention basin facilities are as follows:

- 1 foot of freeboard for basins that have an emergency spillway that is measured from the calculated design water surface elevation to the top of the embankement; or
- 2 foot of freeboard for basins that do not have an emergency spillway that is measured from the calculated design water surface elevation to the top of the embankment.

Where a stormwater basin has an outfall with an emergency spillway, the outfall shall be sized to safely pass the flow from the 10-yr storm and the emergency spillway shall be sized to safely pass the 100-yr storm. For a stormwater basin that does not have an emergency spillway, the outfall shall be sized to safely pass the flow from the 100-yr storm.

For examples of design calculations of outlet structure orifices and weirs, see the VDOT Drainage Manual.

All riser structures shall be cast-in-place, precast concrete, or PVC unless a substitute material has been approved by SID. Standards for riser structures may be found in the VDOT Standards. Riser buoyancy calculations are required.

Outlet pipes shall be reinforced concrete pipe with rubber gasket watertight joints, shall have appropriate seepage control, and shall be installed on a concrete cradle from the toe of the pipe to the riser for the entire length of the outfall pipe. Concrete cradle shall be in accordance with the requirements of the VDOT Standards.

5.2.7 Landscaping

Stormwater basin embankments shall be stabilized. Plant selection and installation shall be in accordance with the standards of the VA Stormwater BMP Clearinghouse website specifications. Trees and shrubs shall not be planted within a stormwater detention basin, nor on a stormwater basin berm, dam, or emergency spillway.

Native plants will be used to the maximum extent possible.

5.2.8 Underground Detention

5.2.8.1 Materials

All materials used in underground detention facilities shall be corrosion-resistant, consisting of reinforced concrete, corrugated high density polyethylene pipe, or similar approved material.

5.2.8.2 Slope

Underground detention facilities shall be sloped to drain at a minimum floor slope of 1 percent.

5.2.8.3 Capacity

Underground detention facilities and other storm drainage system and facility components shall be sized such that the 100-year design storm may be routed through the drainage system and facilities with no damage to the surface property.

5.2.8.4 Accessibility and Maintainability

All underground detention facilities shall be designed to be readily accessible for periodic inspection and maintenance from the surface without the need to perform confined space entry.

Providing pre-treatment to remove sediments before or at the entrance of the underground detention facility to improve water quality and/or improve maintainability shall be included to the maximum extent practicable in the design.

5.2.9 Trash Racks

Outlet structures shall be equipped with an appropriate trash rack. The trash rack shall be in accordance with the VA SWM Handbook.

5.3 Environmental Impacts

Environmental impacts shall be carefully considered when designing stormwater detention facilities. Stormwater detention facilities shall be designed in accordance with MS-14. Proposing basins in low-lying areas with potentially environmentally sensitive areas requires careful consideration, coordination, approval, and permitting with SID and state and federal agencies to evaluate the suitability of constructing in these areas. Environmentally sensitive areas include, but are not limited to wetlands, shallow marshes, jurisdictional waters, natural watercourses, wildlife habitat, etc. and may be protected by state and/or federal laws. With careful planning, it may be possible to incorporate wetland mitigation into the basin design.

Construction of stormwater basins or modifications to existing basins shall comply with all applicable laws and regulations. The applicant is responsible for procuring all necessary permits, such as US Army Corps of Engineers and Virginia DEQ Wetland Permits, Virginia DEQ VPDES Permits, etc., and providing SID with the permit documentation prior to beginning construction.

Detention facilities may be coordinated with a Virginia Tech regional stormwater management facility or the Virginia Tech Stormwater Management Master Plan.

6.0 ENERGY DISSIPATION

Outlet protection for culverts, storm drains, BMP outlets, and steep open channels is essential to prevent high velocity flows from eroding downstream channels and damaging drainage structures. Erosion problems at culverts or at the outlets of detention basins are a common occurrence. Determination of the flow conditions, scour potential, and channel erosion resistance shall be standard procedure for all designs.

Outlet protection can be a channel lining, structure, or flow barrier designed to lower excessive flow velocities and prevent erosion and scour.

Outlet protection shall be employed whenever the velocity of flow at a pipe or open channel outlet exceeds the erosive velocity of the immediate downstream reach.

Energy dissipation may take the form of the following:

- Erosion control stone outlet protection.
- Erosion control stone-lined channels
- Riprap outlet basins
- Concrete baffled outlets

6.1 References

Except where more stringent requirements are presented in this Design Manual, energy dissipators shall comply with VDOT and other state requirements. The primary design references are the VDOT Drainage Manual and the VA ESC Handbook. Other appropriate references include:

- VDOT Road and Bridge Standards
- VDOT Road and Bridge Specifications
- VA Stormwater Management Handbook
- FHWA Design of Riprap Revetment HEC No. 11 (Pub. No. FHWA-IP-89-016 1989/2000)
- FHWA Hydraulic Design of Energy Dissipators for Culverts and Channels HEC No. 14 (Pub. No. FHWA-EPD-86-110 Sept. 1983 & FHWA-IF-00-02 2000)
- U.S. Dept. of the Interior – Bureau of Reclamation: Hydraulic Design of Stilling Basins and Energy Dissipators (Engineering Monograph No. 25)
- U.S. Dept. of the Interior – Bureau of Reclamation: Design of Small Canal Structures

6.2 Design Methodology and Criteria

6.2.1 Outlet Velocity

Where the outlet velocity from culverts, storm drain outfalls, or open channels is high, and channel or pipe modifications cannot adequately reduce the velocity, energy dissipation may be necessary. See the VDOT Drainage Manual and/or the VA ESC Handbook for methodologies to determine design outlet velocities from open channels, culverts, and storm drains.

6.2.2 Erosion Control Stone

The most common form of energy dissipation is the use of erosion control stone at the outlet. Protection is provided primarily by having sufficient length and flare to dissipate energy by expanding the flow. The outlet velocities are computed for the 10-year discharge.

Where a pipe discharges into a channel, the apron shall extend across the channel bottom and shall extend up the bank to a depth of one foot above the maximum tailwater depth from the design storm event. The dimensional requirements of the erosion control stone apron shall be determined using the graphical curves in the VA ESC Handbook.

Generally, the use of erosion control stone for energy dissipation is limited to a maximum velocity of 19 feet per second. Alternative means of energy dissipation shall be required where the discharge velocity is greater than 19 feet per second. Alternative means include riprap stilling basins or concrete baffled outlets. The use of alternative means of energy dissipation requires the approval of VDOT when located in a VDOT right-of-way.

6.2.3 Riprap Basins

A riprap outlet basin is a depressed area of riprap placed at the outlet of a high velocity culvert, storm drain or open channel. The riprap reduces the exit velocity by expanding the flow over the riprap length and width and forming a hydraulic jump.

For the design of riprap basins, refer to the VDOT Drainage Manual. Dissipator geometry may also be computed using the "Energy Dissipator" module that is available in the computer program FHWA HY8, Culvert Analysis.

6.2.4 Baffled Outlets

A baffled outlet usually consists of a concrete box structure with a vertical hanging concrete baffle and an end sill. Several variations of concrete baffled outlets have been published by VDOT and other state and local transportation and stormwater management agencies. Baffled outlets are usually used when very high exit velocities exist at piped or channel transitions. Baffled outlets function by dissipating energy through impact of the water hitting the baffle and through the resulting turbulence. A tailwater depth is not required for adequate energy dissipation, but will help smooth the outlet flow.

This type of outlet protection may be used with outlet velocities up to 50 feet per second.

Baffled outlets are not included in the state guidance handbooks. Hydraulic design procedures for baffled outlets may be found in the U.S. Department of Interior, Bureau of Reclamation, Design of Small Canal Structures, 1978.

6.2.5 Additional Energy Dissipators

For additional energy dissipators, refer to FHWA HEC No 14, Hydraulic Design of Energy Dissipators for Culverts and Channels.

6.3 Installation Requirements

Energy dissipators shall be installed and constructed according to all applicable FHWA, VDOT, and state requirements and recommendations.

6.4 Environmental Impacts

Construction or modifications to energy dissipation structures shall comply with all applicable laws and regulations. The applicant is responsible for procuring all necessary permits, such as US Army Corps of Engineers and VA DEQ Wetland Permits, etc.

6.5 Maintenance Requirements

The Operator is responsible for maintenance of energy dissipation structures in accordance with VESCH standards until the termination of land disturbance as described in the Annual Standards and Specifications.

7.0 STORMWATER POLLUTANT REMOVAL PRACTICES

A wide variety of Best Management Practices (BMPs) and general development strategies may be utilized to remove environmentally harmful pollutants from stormwater runoff. Allowable BMPs are listed on the VA Stormwater BMP Clearinghouse website.

7.1 References

Except where more stringent requirements are presented in this Design Manual, stormwater quality best management practices shall comply with DEQ requirements. The primary design reference is the VA Stormwater BMP Clearinghouse website.

7.2 Stormwater Quality Requirements

Stormwater runoff generated from land disturbing activities shall be treated through best management practices designed to remove pollutants from the stormwater. The required pollutant removal shall be dependent on the land cover conditions.

For most projects, the BMPs will be designed to remove phosphorus from the stormwater runoff. Generally, when a BMP is efficient in removing phosphorus from the stormwater runoff, it is assumed that easier to remove pollutants such as heavy metals and total suspended solids have also been adequately removed.

Where appropriate, additional pollutants may be required to be removed from the stormwater runoff based on the presence of stormwater hotspots (land use activities that generate highly contaminated runoff, as determined by SID). These pollutants may include the following:

- Total Suspended Solids, in areas with highly erodible soils.
- Total Petroleum Hydrocarbons (TPH), fueling stations or areas with fuel- contaminated soil.
- Heavy Metals, in areas with contaminated soils.
- High temperature runoff.

Land disturbing activities shall also comply with all additional water quality requirements as indicated in the Virginia Tech Annual Standards and Specifications, current version.

Proposed Common Plan developments shall apply stormwater quality management criteria to the land development project as a whole. Individual projects in Common Plan developments shall not be considered separate land development projects in regards to water quality. Hydrologic parameters shall reflect the ultimate land development and shall be used in all engineering calculations.

Where stormwater quality requirements must be implemented, stormwater runoff must flow through appropriate BMPs before the water is discharged from the site.

7.3 Stormwater Quality Calculations

To meet the requirements of section 9VAC25-870-65 of the VSMP regulations, the Virginia Runoff Reduction Method (VRRM) will be utilized to verify compliance. The VRRM water quality compliance worksheet is available on the DEQ website. This worksheet must be submitted in the SWM Plan. The average one-year rainfall depth shall be 43 in.

7.4 Manufactured BMP Systems

A manufactured BMP system is a structural measure that is specifically designed and sized by a manufacturer to intercept stormwater runoff and prevent the transfer of pollutants downstream. Use of Manufactured BMPs will only be allowed if the device is approved and listed on the VA Stormwater BMP Clearinghouse website.